

"2001: A Space Odyssey" Revisited -- The Feasibility of 24 Hour Commuter Flights to the Moon Using LOX-Augmented NTR Propulsion

presented by

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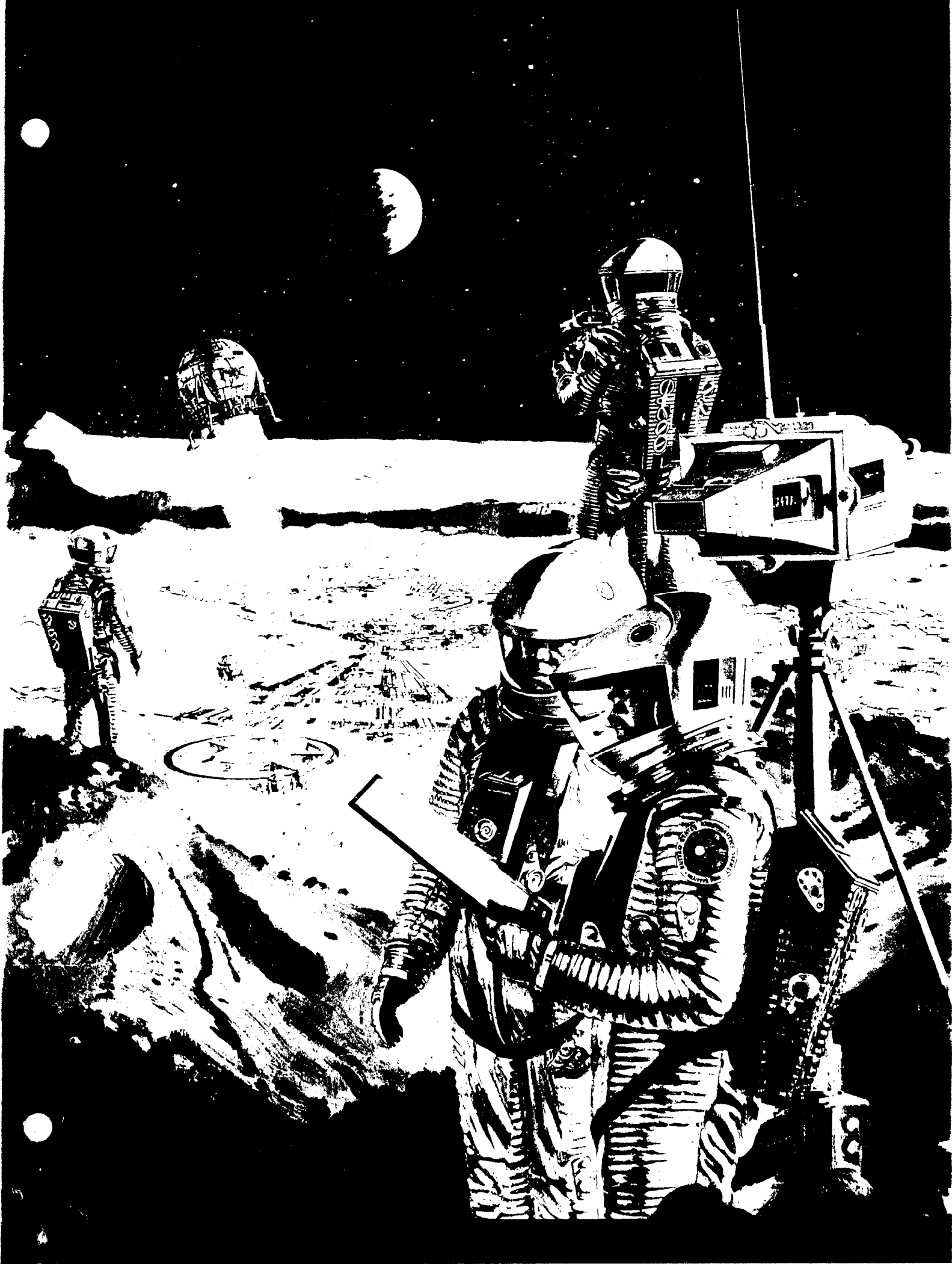
April 3-5, 2001

"2007: A SPACE ODYSSEY" REVISITED -- THE FEASIBILITY OF 24 HOUR
COMMUTER FLIGHTS TO THE MOON USING LOX-AUGMENTED NTR
PROPULSION

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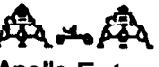
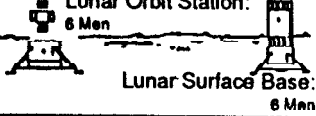

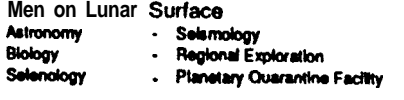
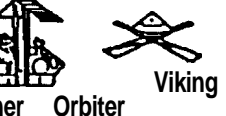






ABSTRACT

The prospects for "24 hour" commuter flights to the Moon, similar to that portrayed in *2001: A Space Odyssey* but on a more Spartan scale, are examined using two near term, "high leverage" technologies -- liquid oxygen (LOX)-augmented nuclear thermal rocket (NTR) propulsion and "lunar-derived" oxygen (LUNOX) production. Iron rich volcanic glass, or "orange soil," discovered during the Apollo 17 mission to the Taurus-Littrow Valley, 'has produced a 4% oxygen yield in recent NASA experiments using hydrogen reduction. LUNOX development and utilization would eliminate the need to transport oxygen supplies from Earth and is expected to dramatically reduce the size, cost and complexity of space transportation systems. The LOX-augmented NTR concept (LANTR) exploits the high performance capability of the conventional liquid hydrogen (LH₂)-cooled NTR and the mission leverage provided by LUNOX in a unique way. LANTR utilizes the large divergent section of its nozzle as an "afterburner" into which oxygen is injected and supersonically combusted with nuclear preheated hydrogen emerging from the engine's choked sonic throat -- essentially "*scramjet propulsion in reverse*." By varying the oxygen-to-hydrogen mixture ratio, the LANTR engine can operate over a wide range of thrust and specific impulse (Isp) values while the reactor core power level remains relatively constant. The thrust augmentation feature of LANTR means that "big engine" performance can be obtained using smaller, more affordable, easier to test NTR engines. The use of high-density LOX in place of low-density LH₂ also reduces hydrogen mass and tank volume resulting in smaller space vehicles. An implementation strategy and evolutionary lunar mission architecture is outlined which utilizes Shuttle-derived heavy lift launch vehicles and conventional NTR-powered lunar transfer vehicles (LTVs), operating in an "expendable mode" initially, to maximize delivered surface payload on each mission. The increased payload is dedicated to installing "modular" LUNOX production units with the intent of supplying LUNOX to lunar landing vehicles (LLVs) and then LTVs at the earliest possible opportunity. Once LUNOX becomes available in low lunar orbit (LLO), monopropellant NTRs would be outfitted with an oxygen propellant module, feed system and afterburner nozzle for "bipropellant" operation. Transition to a "reusable" mission architecture now occurs with smaller, LANTR-powered LTVs delivering -400% more payload on each piloted round trip mission than earlier expendable "all LH₂" NTR systems. As initial lunar outposts grow to eventual lunar settlements and LUNOX production capacity increases, the LANTR concept can enable a rapid "commuter" shuttle capable of 24 hour "one-way" trips to and from the Moon. A vast deposit of "iron-rich" volcanic glass beads identified at just one candidate site -- located at the southeastern edge of Mare Serenitatis -- could supply sufficient LUNOX to support daily commuter flights to the Moon for the next 9000 years!

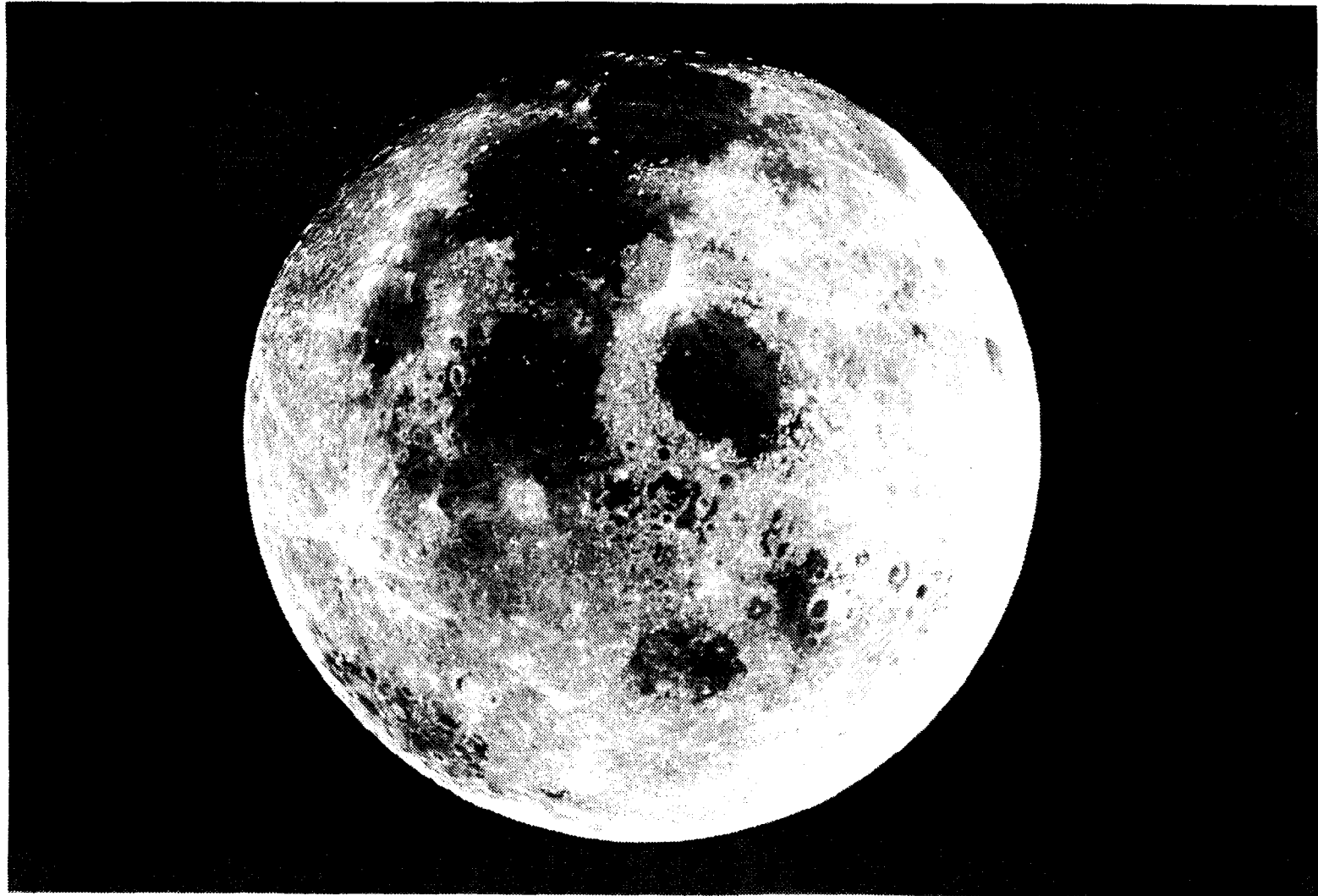




VON BRAUN INTEGRATED SPACE PROGRAM 1970 - 1990

	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89
Earth orbit	 Saturn Workshops					 Space Station					 Geosynchronous Station				 Space Base				<ul style="list-style-type: none"> • 100 Men in Low Earth Orbit • Astronomy • Earth Resources • Life Sciences • Space Physics • Materials Research and Processing 	
Lunar	 Apollo Extended Apollo					 Lunar Orbit Station: 6 Men Lunar Surface Base: 6 Men					 24 Men in Lunar Orbit				 48 Men on Lunar Surface				<ul style="list-style-type: none"> • Astronomy • Biology • Selenology • Seismology • Regional Exploration • Planetary Quarantine Facility 	
Planetary	 Mariner Orbiter Viking					 High Data Rate Orbiter Grand Tour					 Manned Mars Landing				 Semi-Permanent Base Temporary Base: 48 Men on Surface: 12 Men 24 Men in Orbit					
Transportation	 Saturn V Space Shuttle					 TUG Nuclear Shuttle					 Mars Excursion Module									

The Moon--A “Natural” Space / Gas Station for Future Human Activities in the 21st Century



NASA
C-69-00437

NASA Lewis Research Center
Advanced Space Analysis Office

Why Develop and Settle the Moon ?

- It is nearby-- a 3-day trip (or less?) with short communication time between Earth and the Moon : 2.6 seconds round trip.
- Returning there builds on past U.S. experience-- the Apollo Program. Remember that Europe, Japan and especially Russia have yet to accomplish this feat.
- Moon is **21st** Century's "Next Frontier" with a surface area of 38 million **km²**-- 4.2 x that of the continental USA.
- Moon's soil has abundant natural resources-- oxygen (~43% by mass), metals, and ceramics-- for "living off the land." Solar Wind Implanted (SWI) volatiles can also provide source of carbon, nitrogen, hydrogen and helium.
- The Moon offers a large, stable platform free of atmospheric & electromagnetic pollution for studying our own solar system (e.g., the Sun, Earth-Moon origin, etc.)/the universe.
- A lunar base represents the first major step away from Earth /LEO and into the solar system.
- An international lunar initiative will mobilize industry, increase R&T development, enhance scientific knowledge, stimulate education and excite the world's people.

February 12, 1973

Aviation Week & Space Technology

A McGraw-Hill Publication \$1.00

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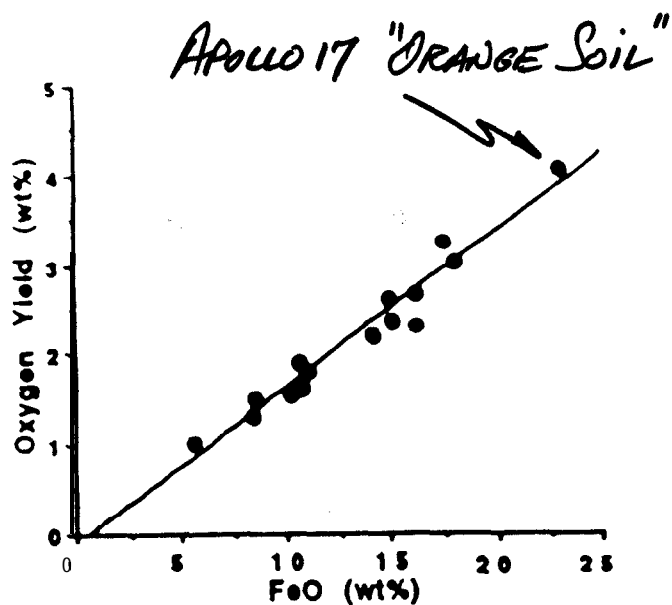


Figure 1. Oxygen yield vs. initial FeO abundance for 15 lunar soils.

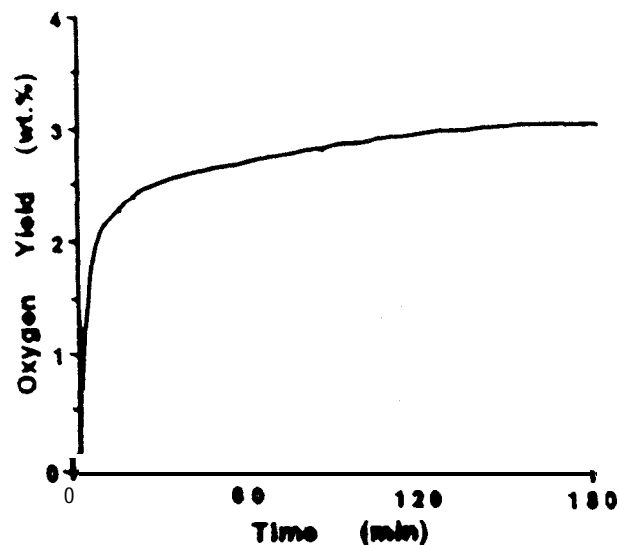


Figure 2. Oxygen yield from lunar soil 75061, reduced at 1050°C.

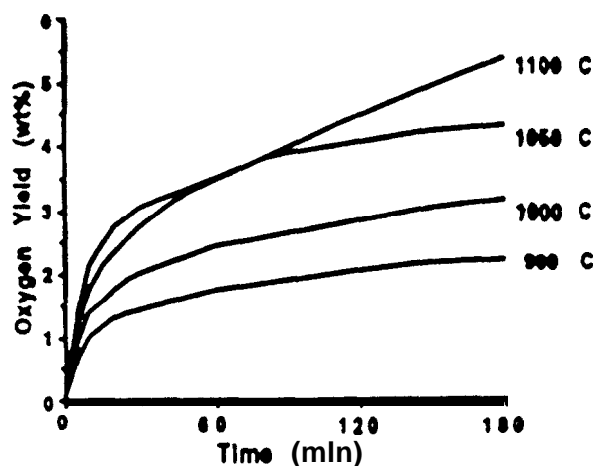
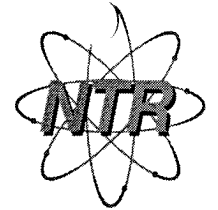


Figure 3. Oxygen yield from lunar volcanic glass 74220, reduced at 900-1100°C.

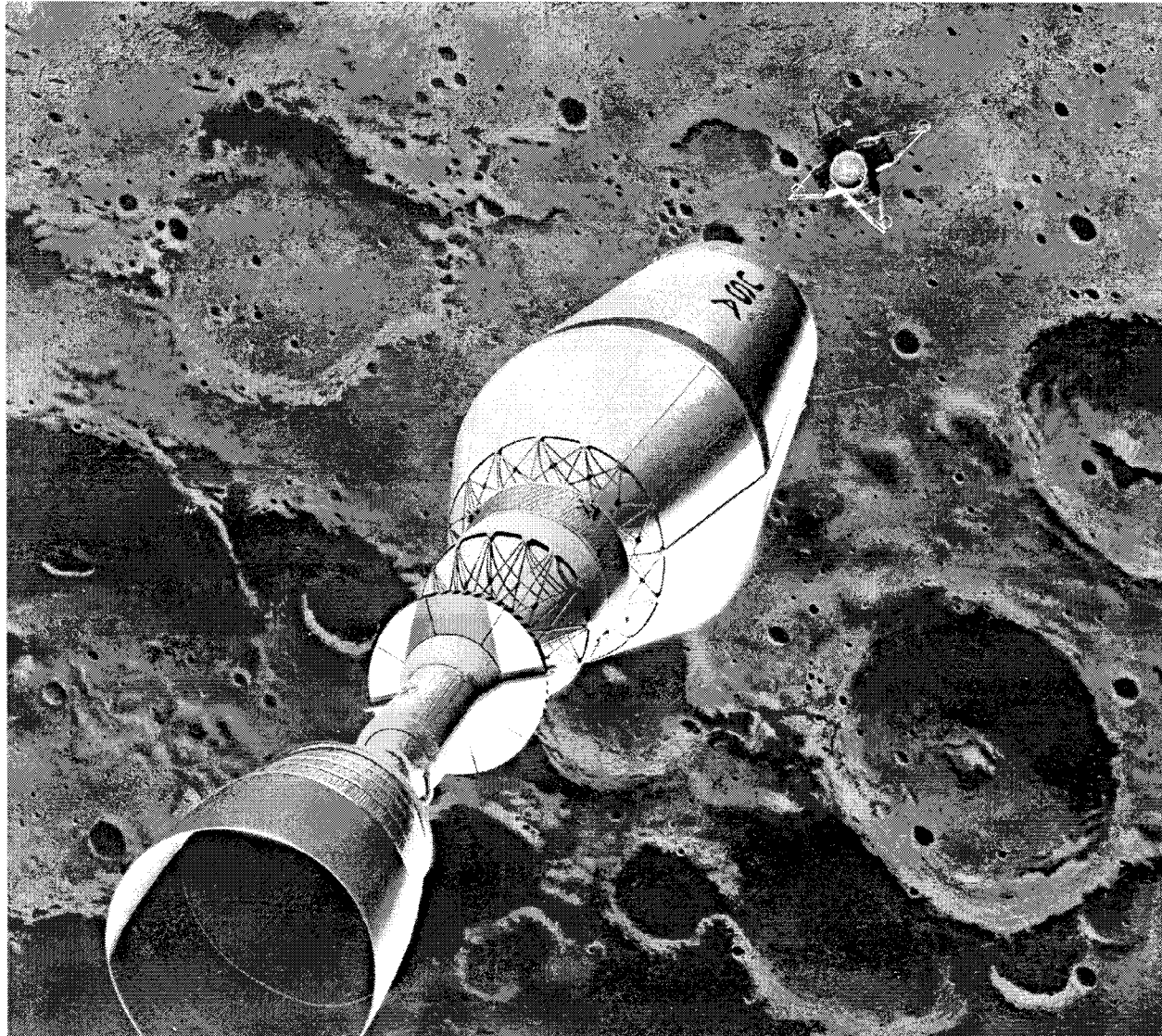
} *APOLLO 17
"ORANGE SOIL"*

Source: Allen & McKay, "Lunar Oxygen Production--
Ground Truth and Remote Sensing," AIAA-95-2792,
31st JPC, San Diego, CA, 10-12 July, 1995

Fully Reusable NTR-Powered Transfer Vehicle “The Key to Affordable Lunar Transportation”

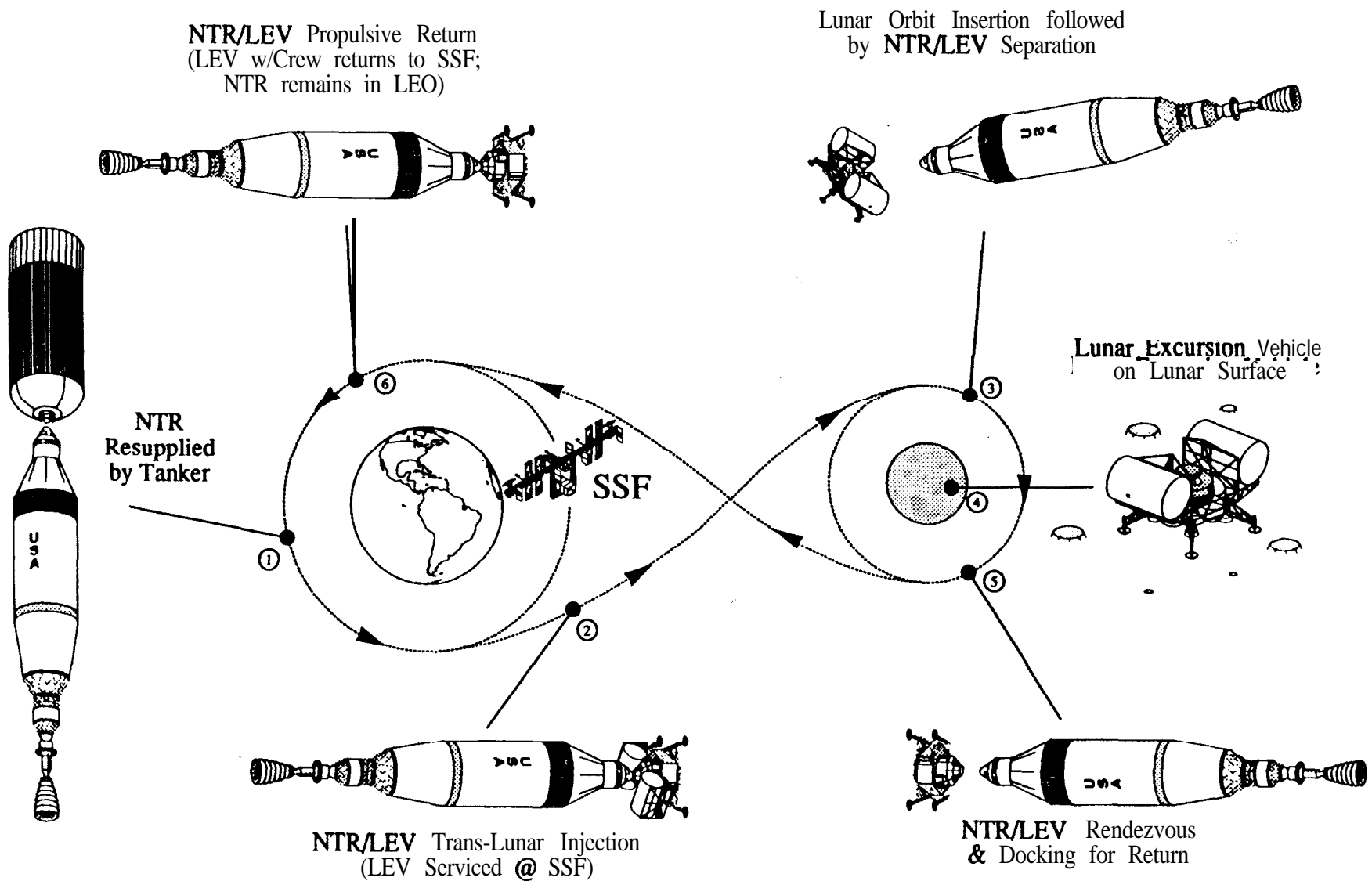


“Propelling Us to New Worlds”

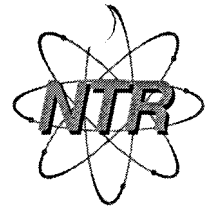


Ref: Borowski, NASA/TM 106739

Fully Reusable Nuclear Thermal Rocket Scenario



Nuclear Thermal Rocket (NTR) Propulsion



What's New?

Then (Rover/NERVA:1959–72)

- **Engine sizes tested**
 - 50–250 klb
- **H₂ exit temps achieved**
 - 2,350–2,550K (Graphite)
- **Isp capability**
 - 825–850 sec (hot bleed)
- **Engine thrust-to-weight**
 - -3 for 75 ktb NERVA

Smaller, Higher
Performance

Easier to test

- **Testing (Rover/NERVA)**
 - “Open Air” exhaust at Nevada test site

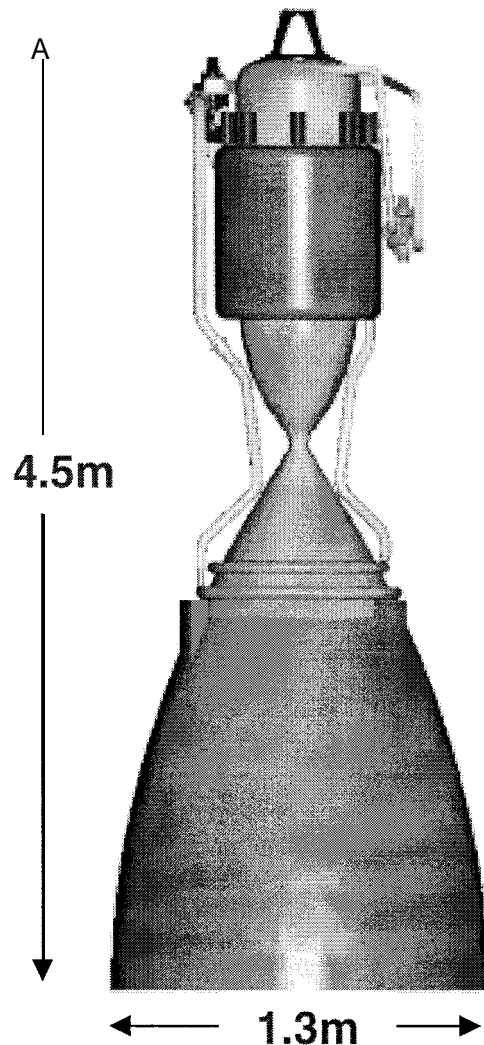
Environmentally
“Green”

For Public
Acceptance

Now

- **“Current” focus is on small NTR**
 - 1 O-I 5 ktb
- **Higher temp. fuels being developed**
 - 2,700K (Cermet) - 3,100K (Tricarbide)
- **Isp capability**
 - 915-955 sec (expander cycle)
- **Advances in chemical rockets/materials**
 - -3-4 for 15 klb small NTR
- **Small NTR allows full power testing in**
 - “Contained Test Facility” at INEL with “scrubbed” H₂ exhaust

Nuclear Thermal Rocket (NTR) Propulsion -- Key Technology / Mission Features --

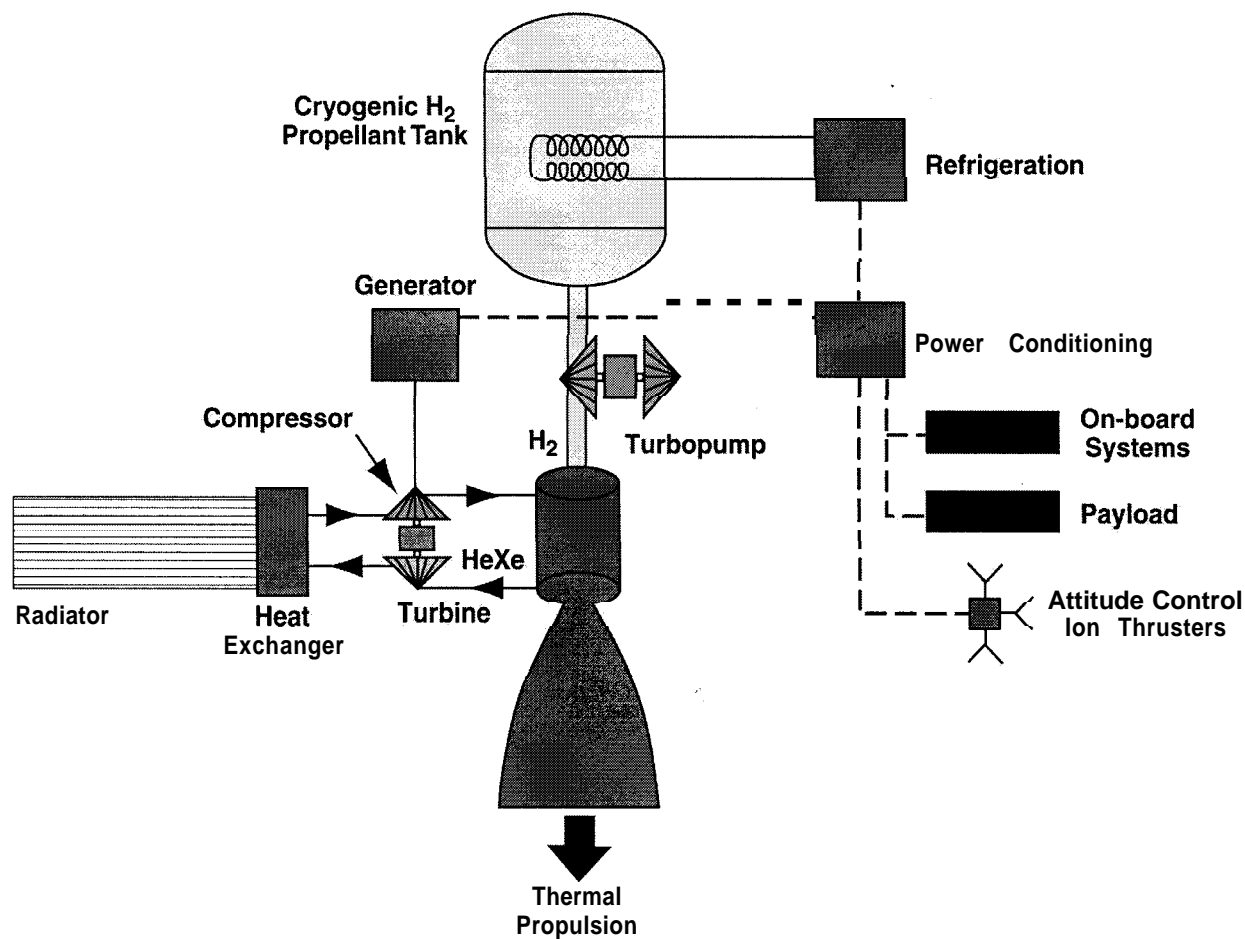


15 klb_f NTR

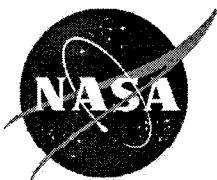
- NTR engines have negligible radioactivity at launch / simplifies handling and stage processing activities at KSC
 - 2.5 Curies / 3 NTR Mars stage vs -400,000 Curies in Cassini's 3 RTGs
- High thrust / Isp NTR uses same technologies as chemical rockets
- Short burn durations (~25-50 mins) and rapid LEO departure
- Less propellant mass than all chemical implies fewer Magnum launches
- NTR engines can be configured for both propulsive thrust and electric power generation -- "bimodal" operation
- Fewest mission elements and much simpler space operations
- Engine size aimed at maximizing mission versatility
 - robotic science, Moon, Mars and NEA missions
- NTR technology is evolvable to reusability and "in-situ" resource utilization (e.g., LANTR -- NTR with LOX "afterburner" nozzle)

"Smarter Systems Engineering"

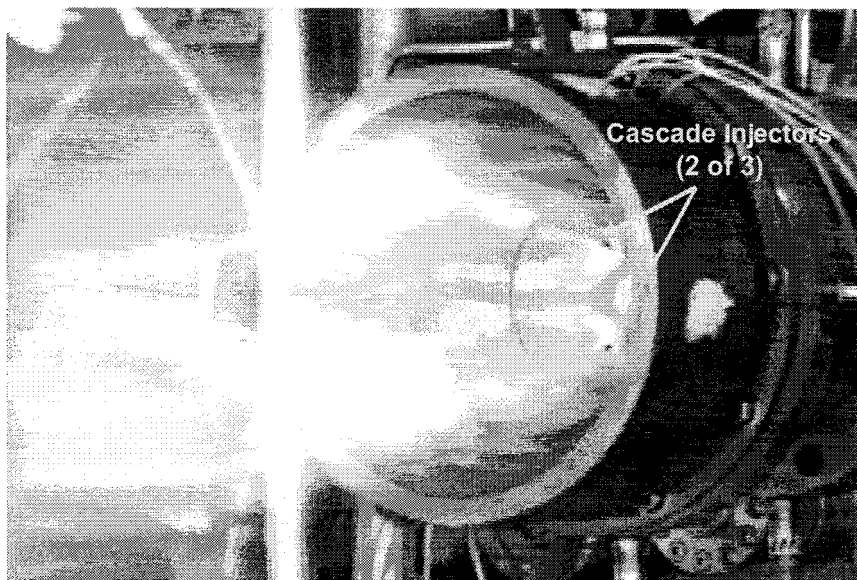
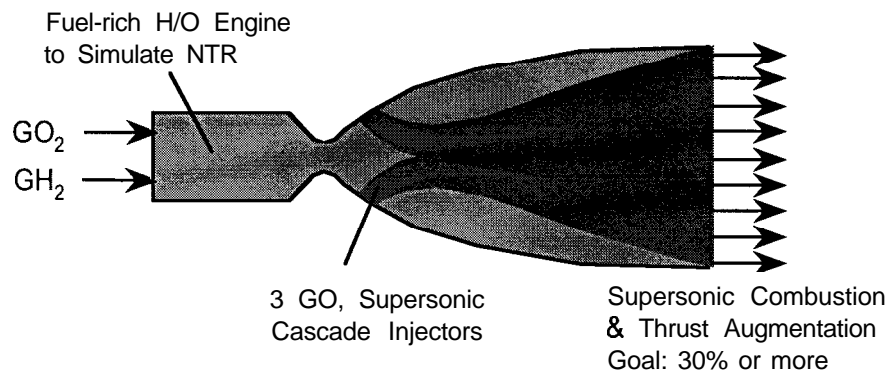
Bimodal NTR-A Fully Integrated Propulsion and Power System



- During power generation, each BNTR operates in "idle mode" producing -110 thermal kilowatts.
- Brayton conversion unit produces up to 25 kilowatts electric to enhance stage capabilities.



“LOX-Augmented” Nuclear Thermal Rocket (LANTR) Proof-of-Concept Demonstration



Baseline H₂O Thrust: 2100 lbf at 1000 psia and MR = 1.0. With GO, injection into nozzle, measured thrust due to supersonic combustion is 3000 lbf (-43% thrust augmentation achieved at MR_L -2.2)

• LANTR Concept I Benefits

- Enhanced NTR with “afterburner” nozzle feature that increases thrust by injecting & combusting GO, downstream of the NTR throat
- Enables NTR with variable thrust and Isp capability by varying nozzle O/H mixture ratio

• Test Objectives

- Measure thrust augmentation from oxygen injection and supersonic combustion using “non-nuclear” experimental demonstrator

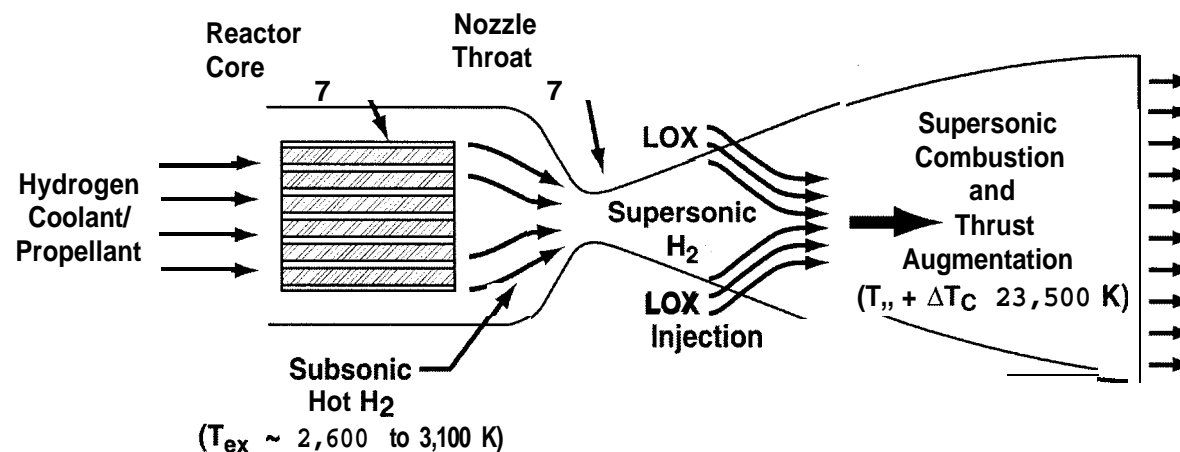
• Status

- LANTR afterburner nozzle demonstrated
 - Oxygen injection into hot supersonic flow
 - Supersonic combustion in the nozzle
 - Elevated nozzle pressures measured
 - Benign nozzle wall environment observed
- Thrust augmentation >40% measured

• Plans

- Complete post test analysis of individual LANTR hot fire tests (63)
- Prepare for higher area ratio testing in FY'01

“LOX-Augmented” NTR (LANTR) Concept --Operational Features and Characteristics--



	I_{sp} (sec)				
Life (hrs)	5	10	35	Tankage Fraction (%)	T/W_{eng} Ratio
T_{ex} (°K)	2,900	2,800	2,600		
O/H MR = 0.0	941	925	891	14.0	3.0*
1.0	772	762	741	7.4	4.8
3.0	647	642	631	4.1	8.2
5.0	576	573	566	3.0	11.0
7.0	514	512	508	2.5	13.1

*For 15 klbf LANTR with chamber pressure = 2,000 psia and $\epsilon = 500$ to 1

“LOX-Augmented” NTR (LANTR) Concept --Engine, Vehicle and Mission Benefits--

- **LANTR couples a reverse scramjet “LOX-afterburner” nozzle to a conventional LH₂-cooled NTR to achieve the following benefits:**
 - Smaller, cheaper NTR’s with “big engine” performance
 - Smaller, cheaper facilities for “contained” ground testing
 - Variable thrust and I_{sp} capability from constant power NTR
 - Shortened burn times and extended engine life
 - Reduced LH₂ propellant tank size, mass, and boil-off
 - Reduced stage size allowing smaller launch vehicles
 - Increased operational range-ability to utilize extraterrestrial sources of O₂ and H₂ (e.g., LUNOX and polar ice, Phobos H₂O, Martian CO₂ and H₂O, and H₂O from “main-belt” asteroids and Jupiter’s moons) can facilitate human expansion into the Solar System

Implementation Approach for “LANTR-Based” Lunar Mission Scenario

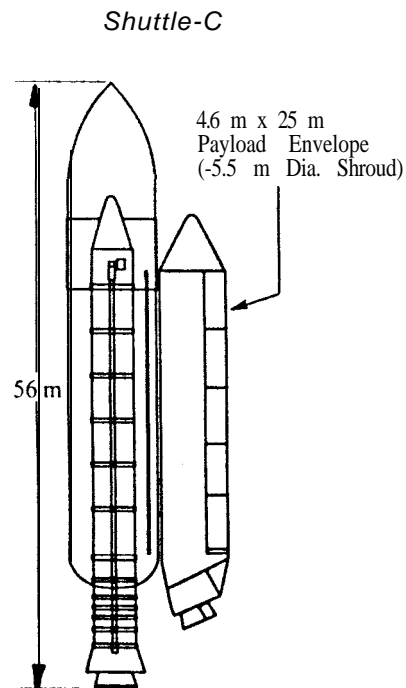
• Objectives:

- Reduce “up-front” investment costs for “in-space” infrastructure
- Eliminate need for developing new 120 - **240-class** HLLV--major cost element (~10 - 15 B\$) of LTS
- Maximize surface payload per lunar landing mission
- Minimize LTS “recurring costs” so that commercialization and human settlement of the Moon can become practical

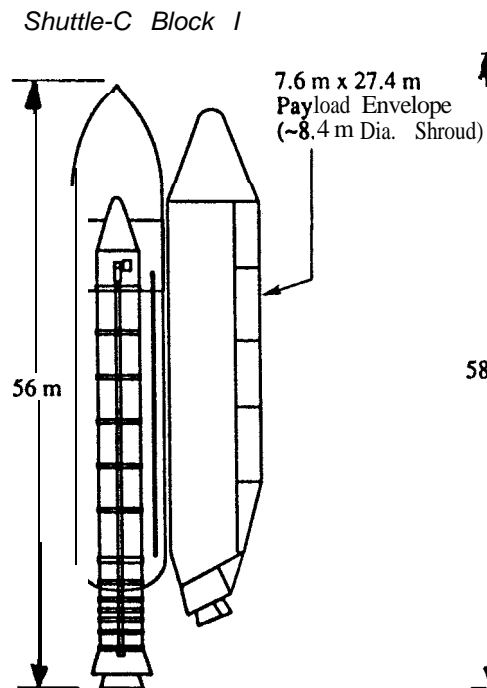


- Utilize “all LH,” NTR-powered LTV operating initially in “expendable mode”
- Expendable approach reduces support infrastructure, IMLEO / allows use of Shuttle C or “Shuttle-derived” vehicle (SDV) for Earth-to-orbit lift
- Cargo mission(s) precede piloted with surface payloads “dedicated” primarily to LUNOX production and habitation requirements
- LUNOX used for refueling LLVs initially, then LANTR-powered LTVs
 - Transitioning to “reusable” LTS architecture @ earliest possible date improves life cycle costs
 - Accumulated cost savings invested “gradually” in infrastructure

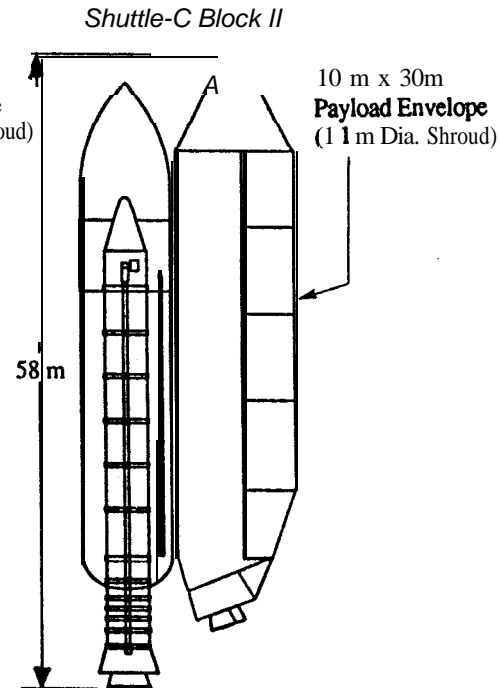
Lunar Launch Vehicle Options



2 x ASRM's
Std. ET
3 x 104% SSME's
7 t P/L Capability

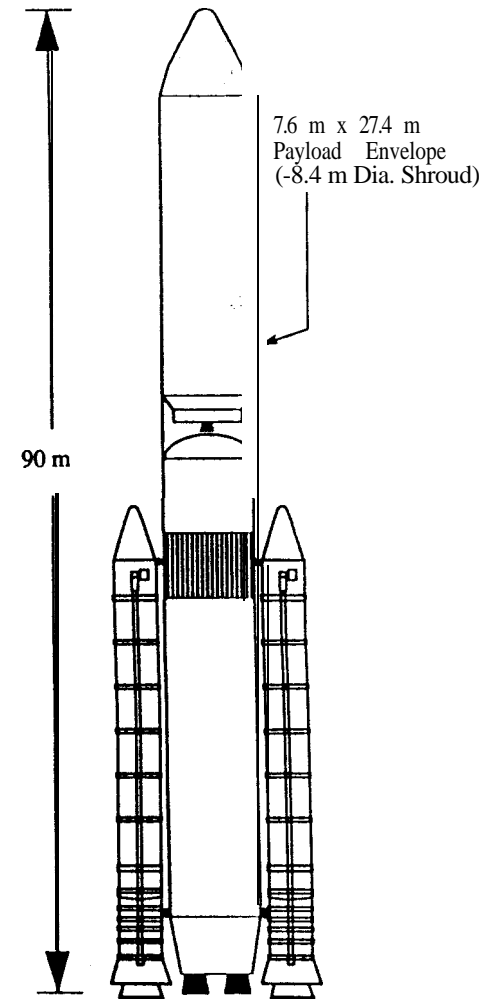


2 x ASRM's
Std. ET
3 x 104% SSME's
61 t P/L Capability



2 x ASRM's (or LRB's)
Mod. ET (Std. Prop. Load)
3 x 104% SSME's
57 t (ASRM)/62 t (LRB)

"In-Line" Shuttle-Derived



2 x ASRM's
Mod. ET
3 or 4 SSME's
66 t P/L Capability

Table 1. Reference Lunar Mission Ground Rules and Assumptions

• Payload Outbound:	9.9 t	LTV crew module
	0.8 t	Crew (4) and suits
	5.0 • 10.0 t	Lunar surface payload
	5.0 t	LLV crew module
	35.7 • 46.0 t	“Wet” LLV stage
• Payload Inbound:	9.9 t	LTV crew vehicle
	0.8 t	Crew (4) and suits
	0.5 t	Lunar samples
• Parking Orbits:	407 km	Circular (Earth Departure)
	300 km	Circular (lunar arrival/departure)
• Trans-lunar injection AV assumed to be 3100 m/s + g-losses		
• Lunar orbit capture/trans-Earth injection ΔV 's assumed to be 915 m/s		
• Earth return: Direct capsule entry		
• Earth gravity assist disposal AV assumed to be 194 m/s (for NTR missions)		
• Mission duration: 54 days' (2 in LEO, 7 in transit, 45 days at Moon)		
• ETO type/payload capability: Shuttle C or SDV / 66 t to 407 km circular		
• LTV assembly scenario: 2 ETO launches with EOR&D (IMLEO < 132 t)		

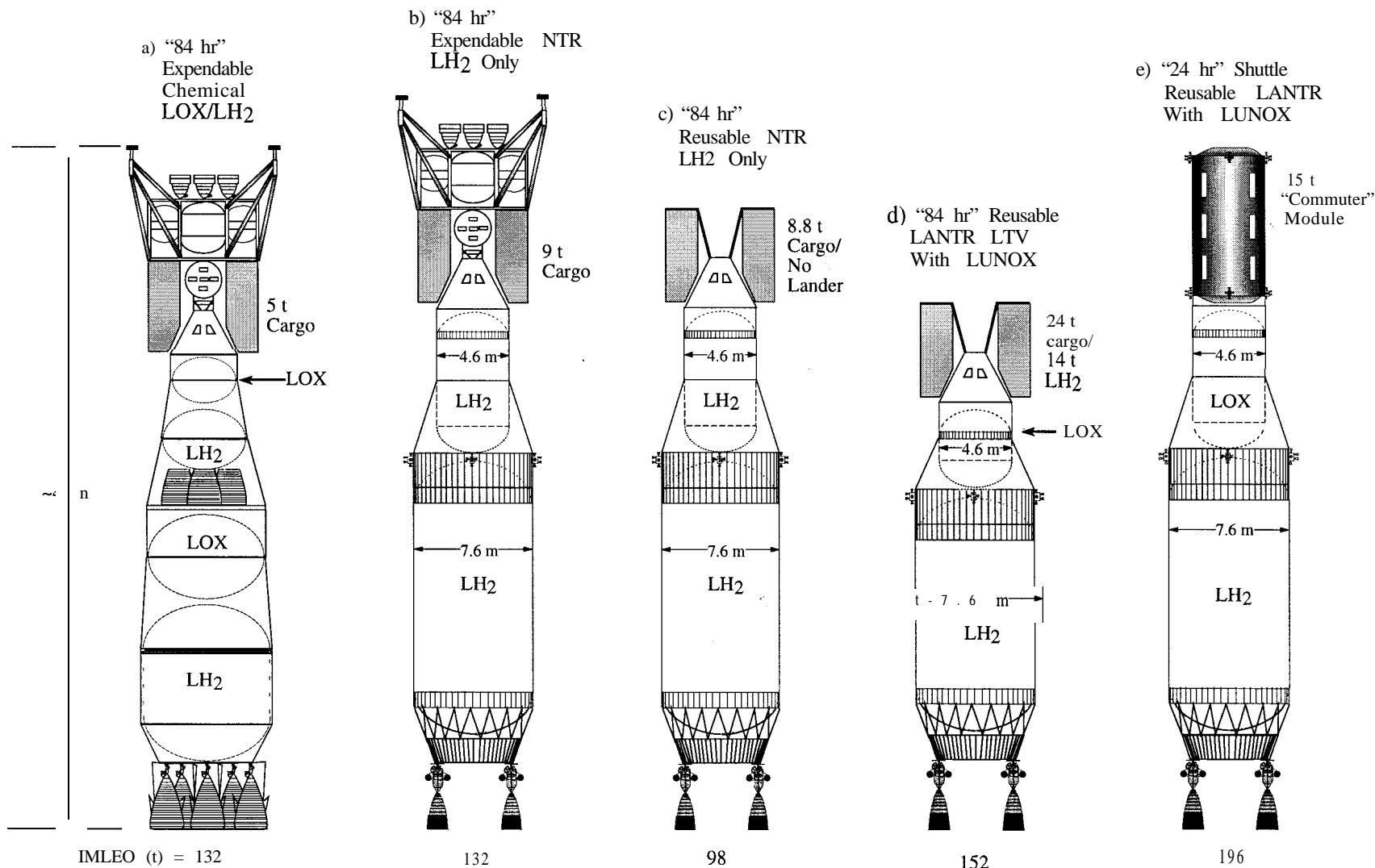
'Chemical TLI and NTR “core” stages in LEO for 30 days prior to second ETO launch.

Table 2. Lunar NTR / LANTR Transportation System Assumptions

• NTR / LANTR: Systems:	Thrust /Weight	= 15 klbf/4904 lbm (LH ₂ NTR)
		= 15 klbf/5797 lbm (LANTR @ MR=0.0)
	Fuel / Propellants	= Tricarbide/Cryogenic LH ₂ & LOX
	Isp	= 940 s (@ O/F MR = 0.0/LH ₂ only)
		= 647 s (@ O/F MR = 3.0)
		= 514 s (@ O/F MR = 7.0)
	External Shield Mass	= 2.84 kg/MWt of reactor power
	Flight Reserve	= 1% of total tank capacity
	Residual	= 1.5% of total tank capacity
	Cooldown (effective)	= 3% of usable LH ₂ propellant
• RCS System:	Propellant	= N ₂ O ₄ /MMH
	Isp	= 320 s
	Tankage	= 5% of total RCS propellants
• Cryogenic Tankage:	Material	= “Weldalite” Al/Li alloy
	Diameter	= 4.6 • 7.6 m
	Geometry	= Cylindrical tanks with $\sqrt{2}/2$ domes
	Insulation	= 2 inches MLI + micrometeoroid debris shield
	LH ₂ /LOX Boiloff*	= 1.31/2.44 kg/m ² /month (LEO @ ~ 240K)
		= 0.56/0.90 kg/m ² /month (in-space @ ~ 172 K)
		= 1.91/3.68 kg/m ² /month (LLO @ ~ 272 K)
• Contingency	Engines, shields and stage dry mass	= 15%

*Assumes 3 x “Lockheed Eqn” heat flux estimates for MLI At ~ 2 inches

Evolution of NTR-Based Lunar Transportation System With LUNOX Development & Utilization



TLI & LOI ΔV vs One-Way TOF - 300 km Lunar Orbit

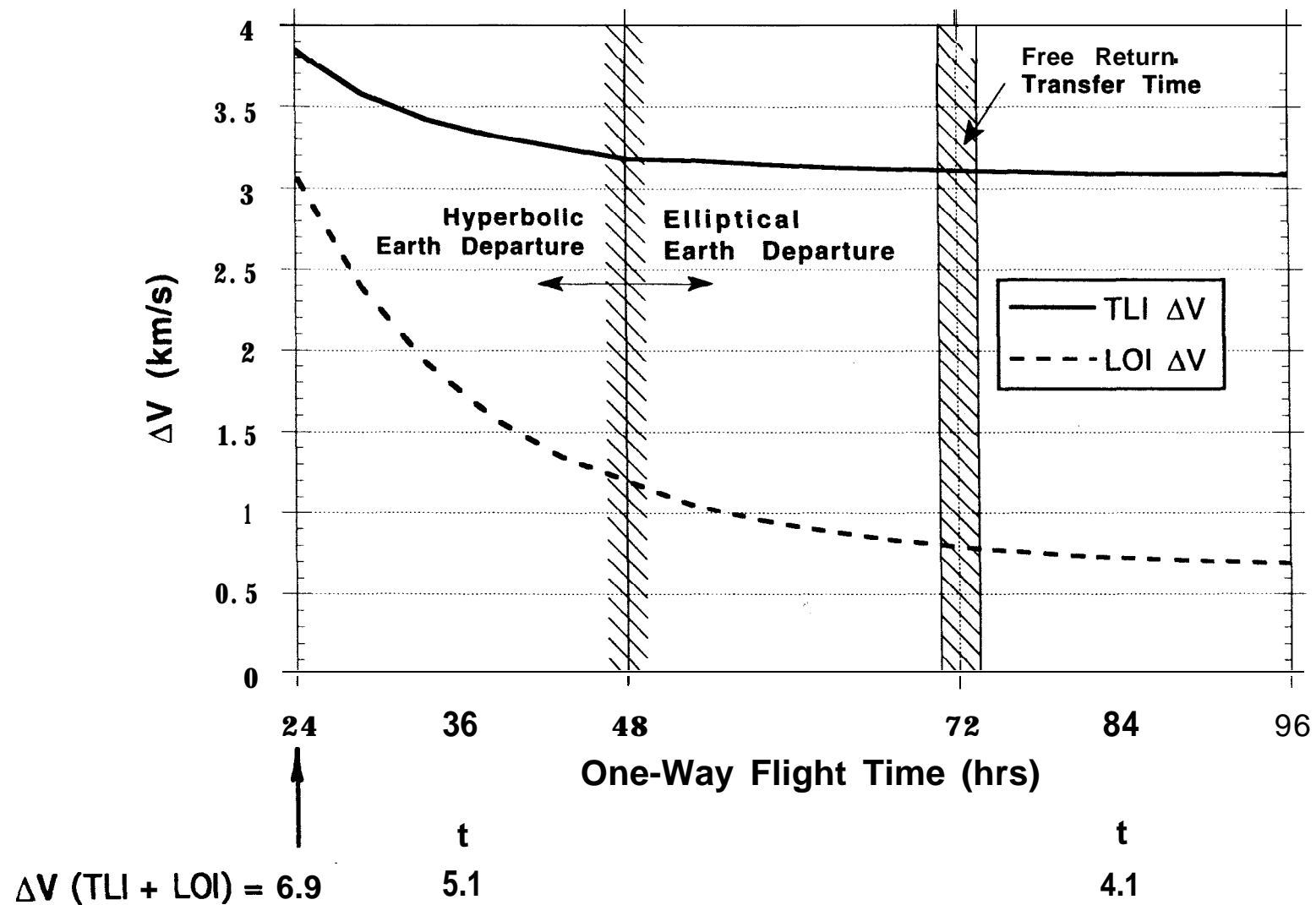


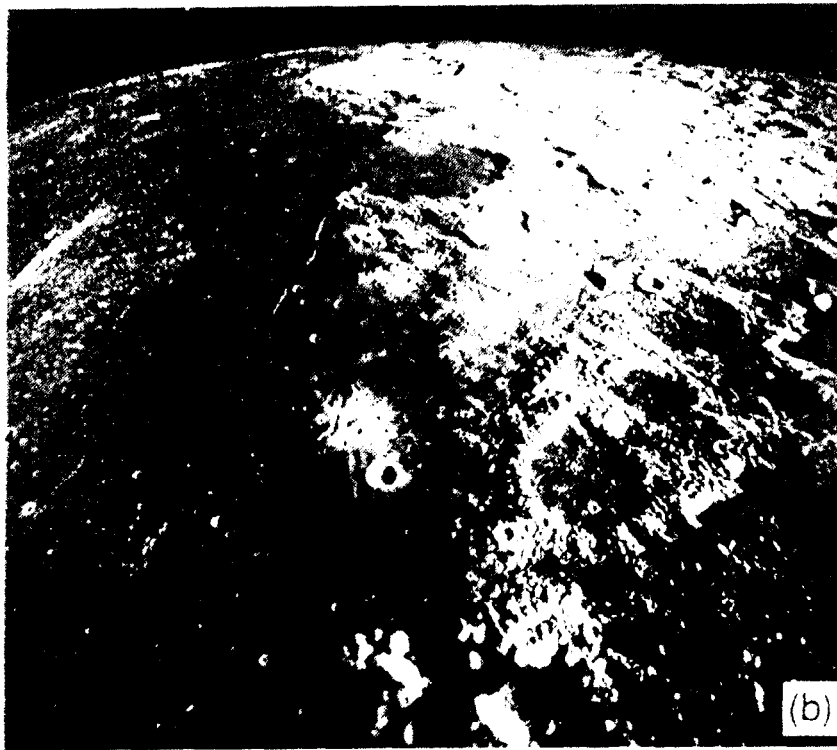
Table 3. LUNOX Requirements for "24 Hour" Commuter Flights to the Moon

24 Hour "1-way" Transits (15 t / 20 Passenger Transport Module):		
LTV: (94.0 t LUNOX / mission*) x 52 weeks / year		= 4888 t / year
LLV: (28.8 t LUNOX / flight+) x (1 flight / LLV / week)		
x 4 LLVs x 52 weeks / year		= 5990 t / year
Total LUNOX Rate		= 10878 t / year

*Assumes LUNOX Usage on 'Moon-to-Earth' Transit only		
+Assumes LLV Transports -25 t of LUNOX to LLO and Returns to Lunar Surface with Empty 5 t "Mobile" LUNOX Tanker Vehicle		

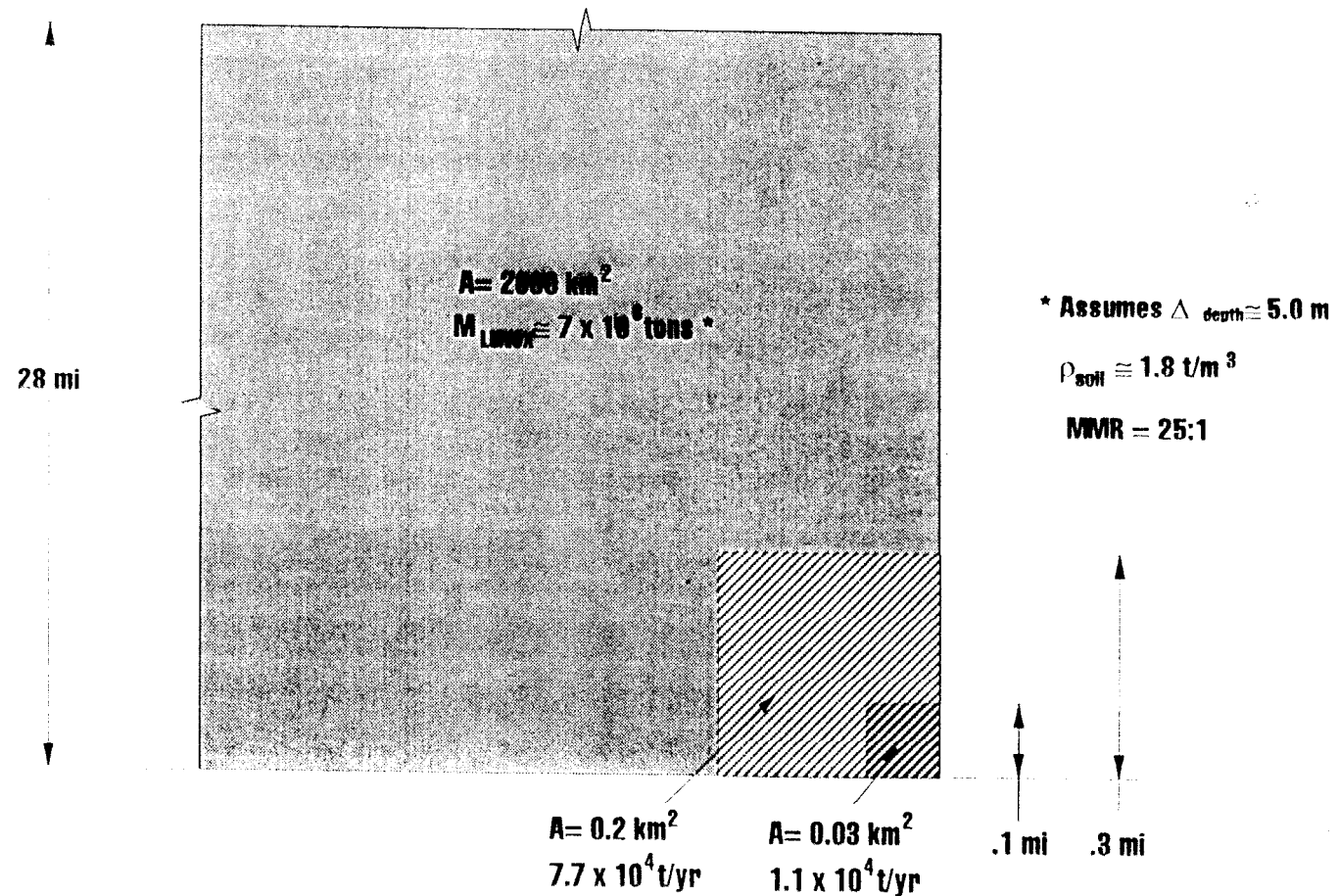
Table 4. Comparison of Different Lunar Mining Concepts
--Plant Mass, Power and Regolith Throughput--

• Hydrogen Reduction of Ilmenite⁷: (LUNOX Production @ 1000 t/year)		
• Plant Mass (Mining, Beneficiation, Processing & Power)		=244 t
• Power Requirements (Mining, Beneficiation & Processing)		=3.0 MWe
• Regolith Throughput (assumes soil feedstock @ 7.5 wt% ilmenite & mining mass ratio (MMR) of 327 t of soil per ton of LUNOX)		=2.3x10 ⁵ t/yr
• Hydrogen Reduction of Iron-rich Volcanic Glass: (LUNOX Production @ 1000 t/yr)		
• Plant Mass (Mining, 'limited' Beneficiation, Processing & Power)		=167 t
• Power Requirements (Mining, "limited" Beneficiation & Processing)		=2.4 MWe
• Regolith Throughput ('limited' beneficiation, direct processing of volcanic glass ('orange soil') with 4% O ₂ yield & MMR = 25 to 1)		=2.5x10 ⁴ t/yr
• Lunar Helium-3 Extraction: (5000 kg (5 t) He ³ /year)		
• Mobile Miners (150 miners required each weighing 18 t / each miner produces 33 kg He ³ per year)		= 2700 t
• Power Requirements (200 kW direct solar power/miner)		= 30.0 MW
• Regolith Throughput (processing & capture of Solar Wind Implanted (SWI) volatiles occurs aboard the miner)		=7.1x10 ⁶ t/yr



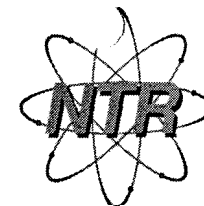
This dark deposit (arrows) at the edge of Mare Serenitatis is composed of volcanic glass beads. It could be a prime site for oxygen production to support a future lunar base. The deposit covers thousands of square kilometers and is tens of meters thick. The Apollo 17 astronauts explored the Taurus Littrow valley near the bottom edge of this picture.

Mining Area and LUNOX Production Rates to Support “24 Hour” Commuter Flights to the Moon

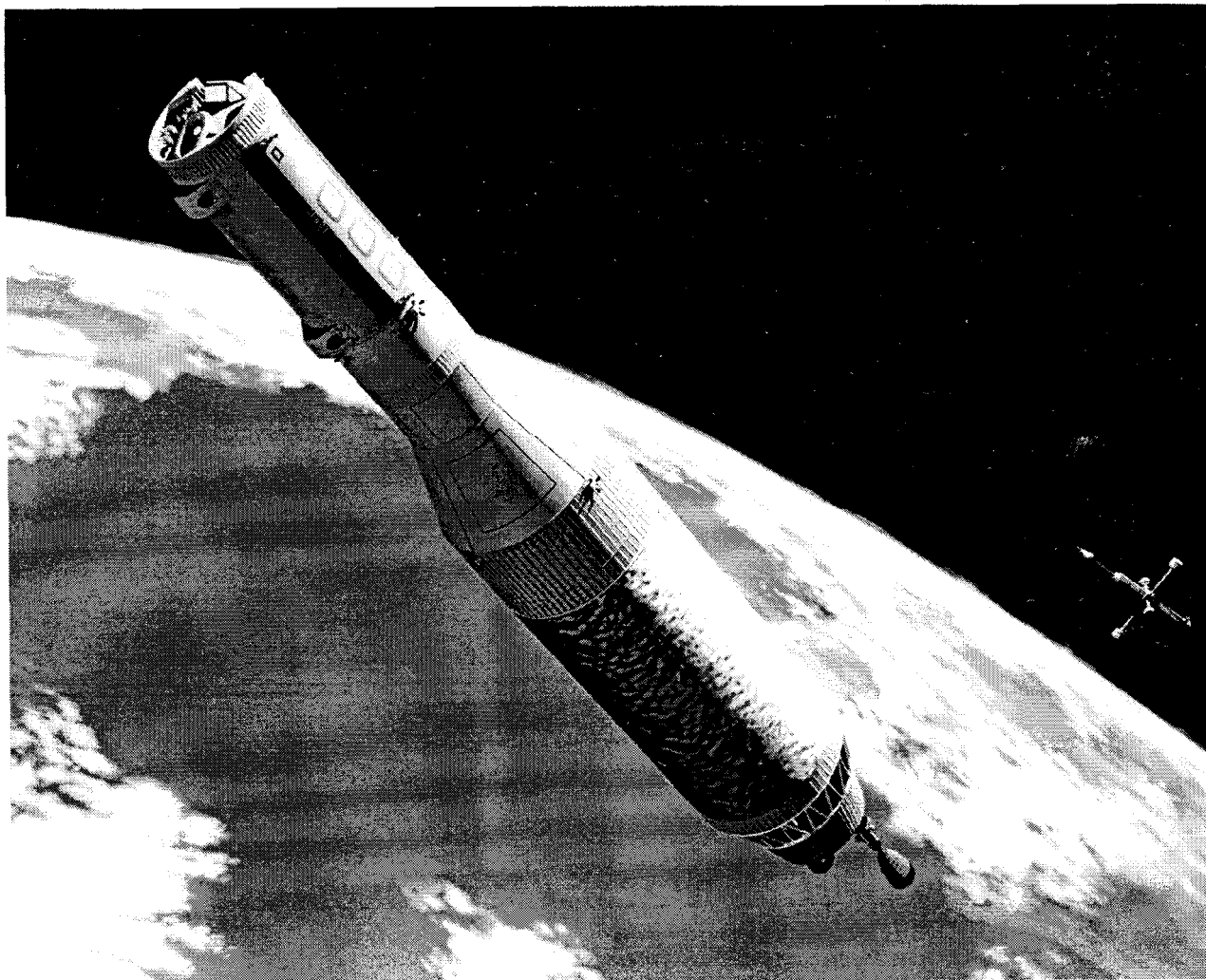


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ADVANCED MISSION ANALYSIS TEAM

“24 Hour” Commuter Flight to the Moon Using LOX-Augmented NTR (LANTR) Transfer Vehicle



“Propelling Us to New Worlds”



20 person Passenger Transport Module (PTM) departs LEO aboard a reusable LANTR-powered Lunar Transfer Vehicle (LTV)

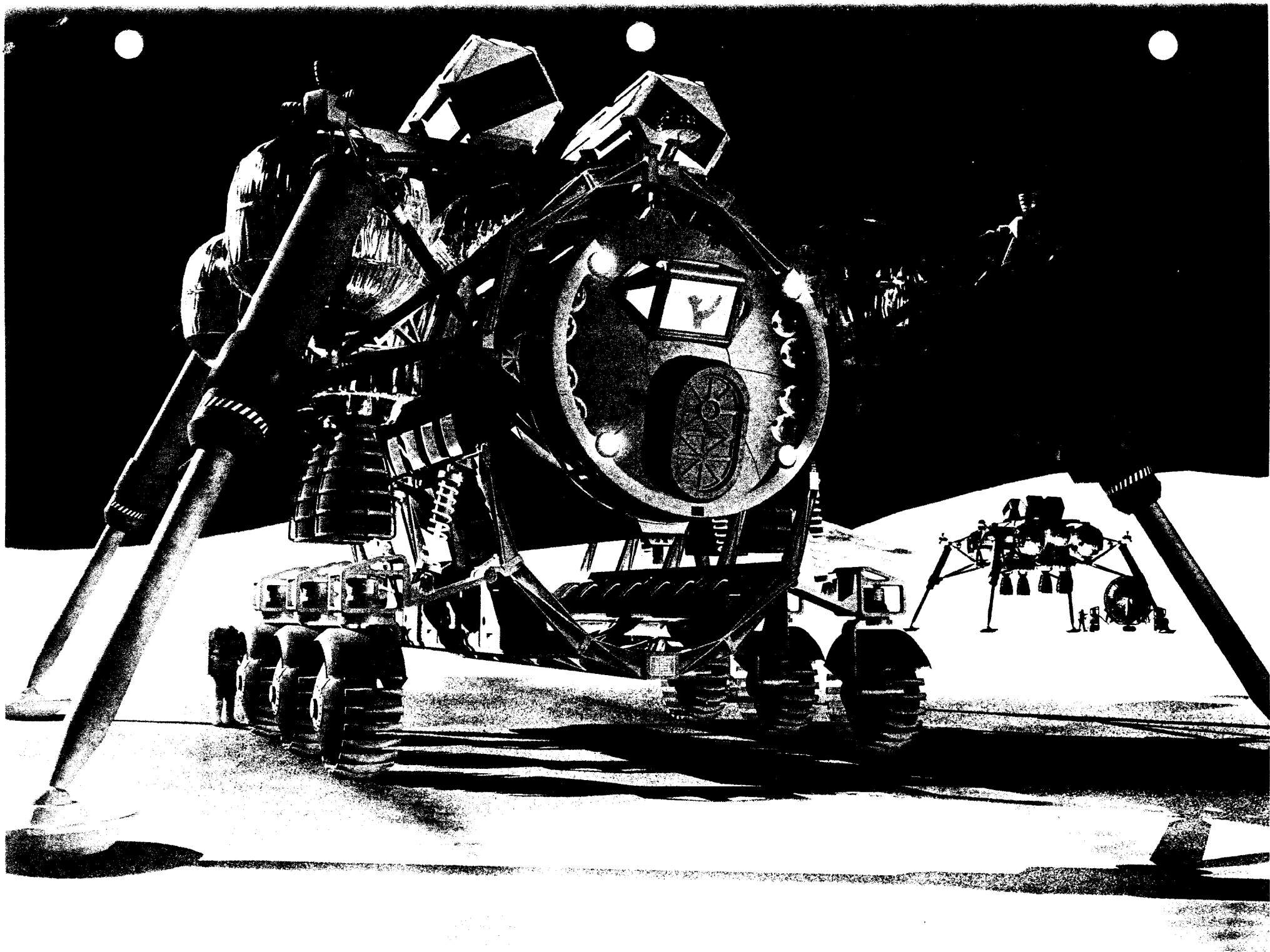


EXPLORATION
Transportation

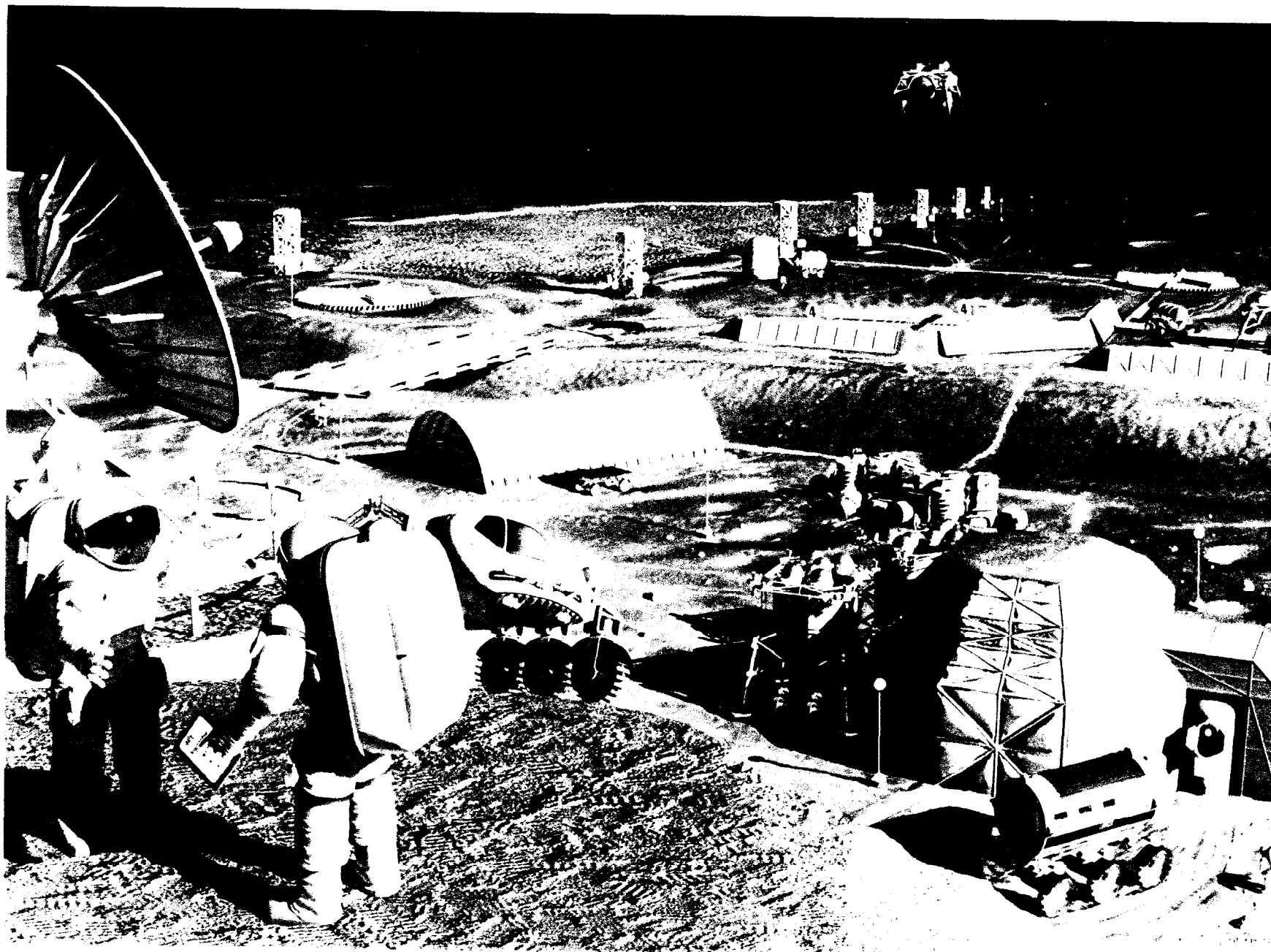
Ref: Borowski et al., NASA/TM--1998-208830

SKB / ASPW - 2001, April 3-5, 2001

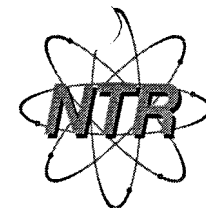




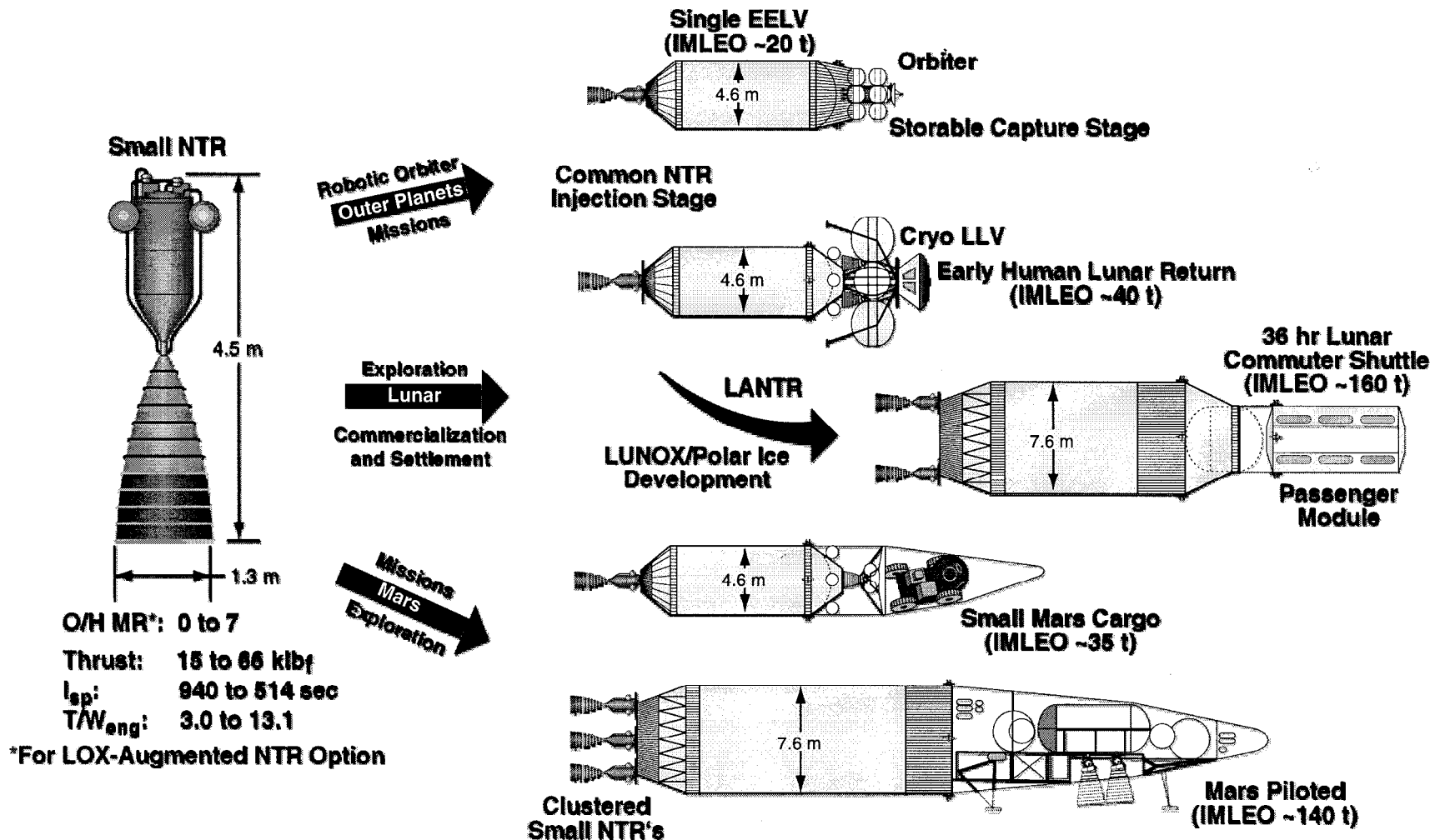




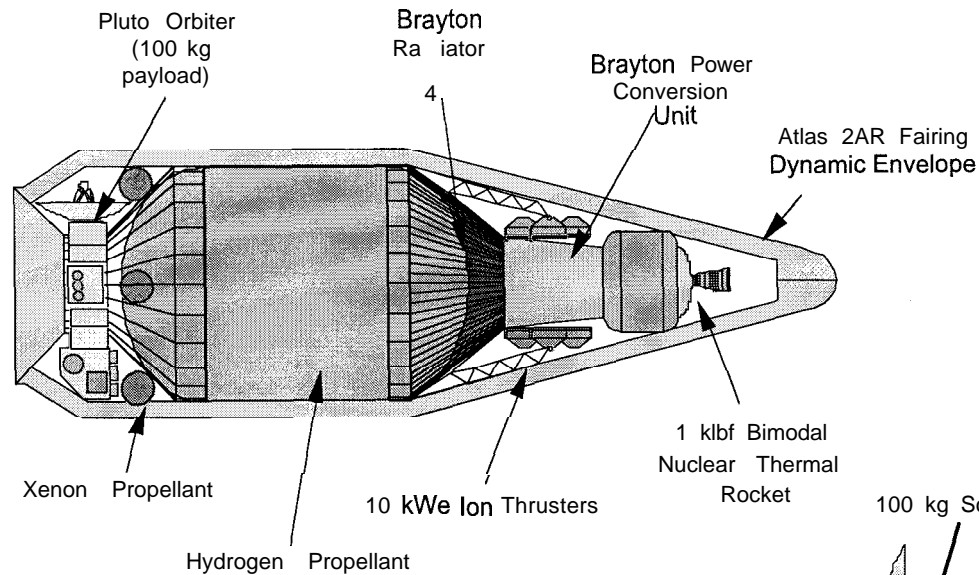
Small NTR - Increases Mission Versatility "One Size Fits All"



"Propelling Us to New Worlds"

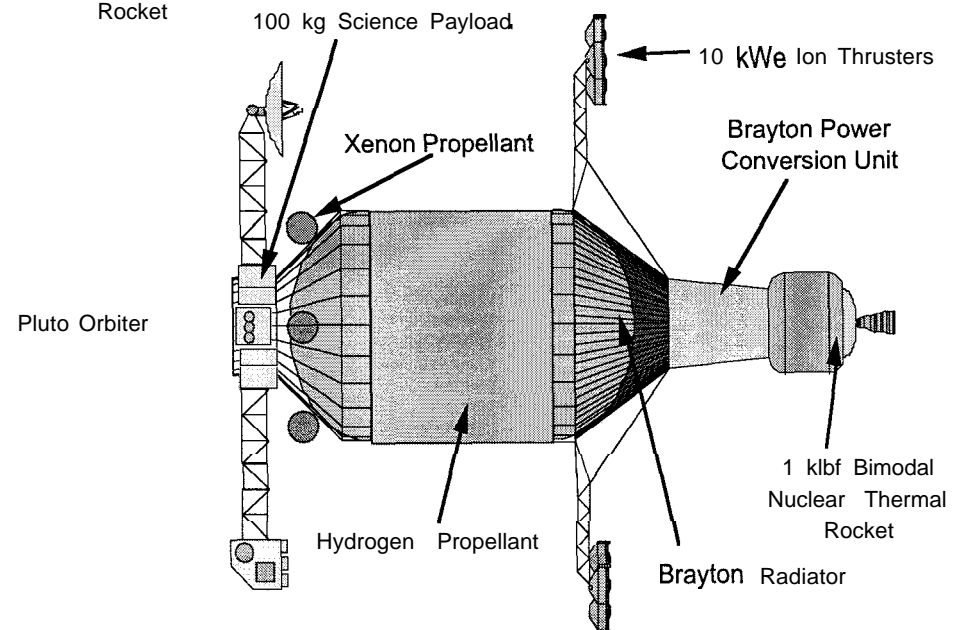


Small Bimodal Nuclear Thermal Rocket / Electric Propulsion Hybrid Vehicle for Outer Planet Exploration



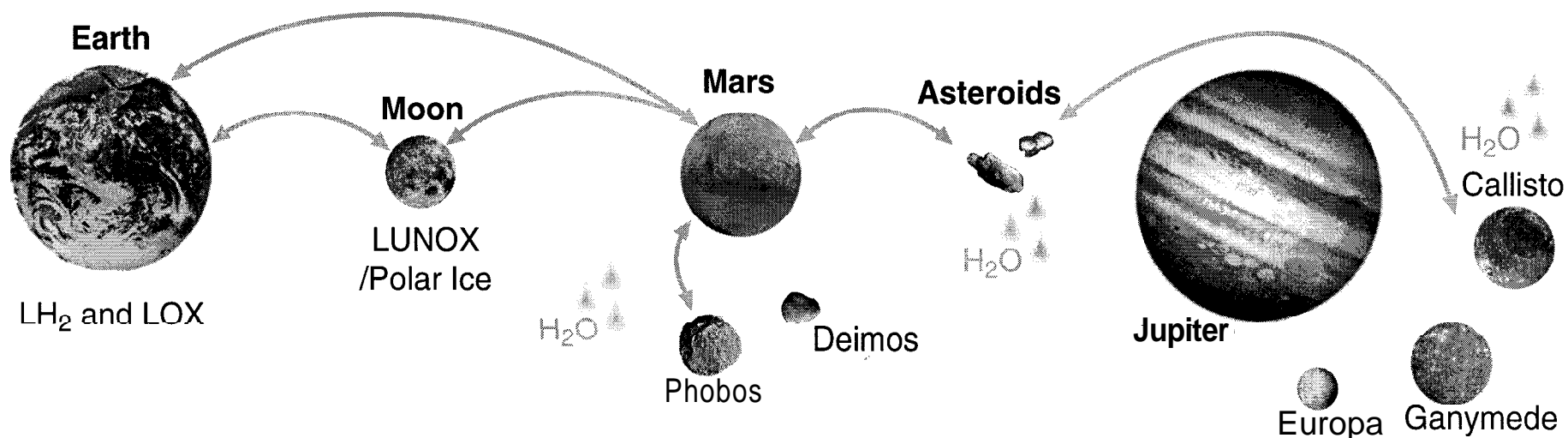
Features:

- Single 1.0 klb NTR engine
- 20 kWe power system
- 2 sets of 10 kWe ion thrusters
- Pluto orbiter w/100 kg payload
- Atlas 2AR (III) launch
- Other outer planet orbiter missions



Human Exploration Possibilities Using NTR

High thrust and I_{sp} , power generation and ISRU allow significant downstream growth capability--"Revolution through Evolution"

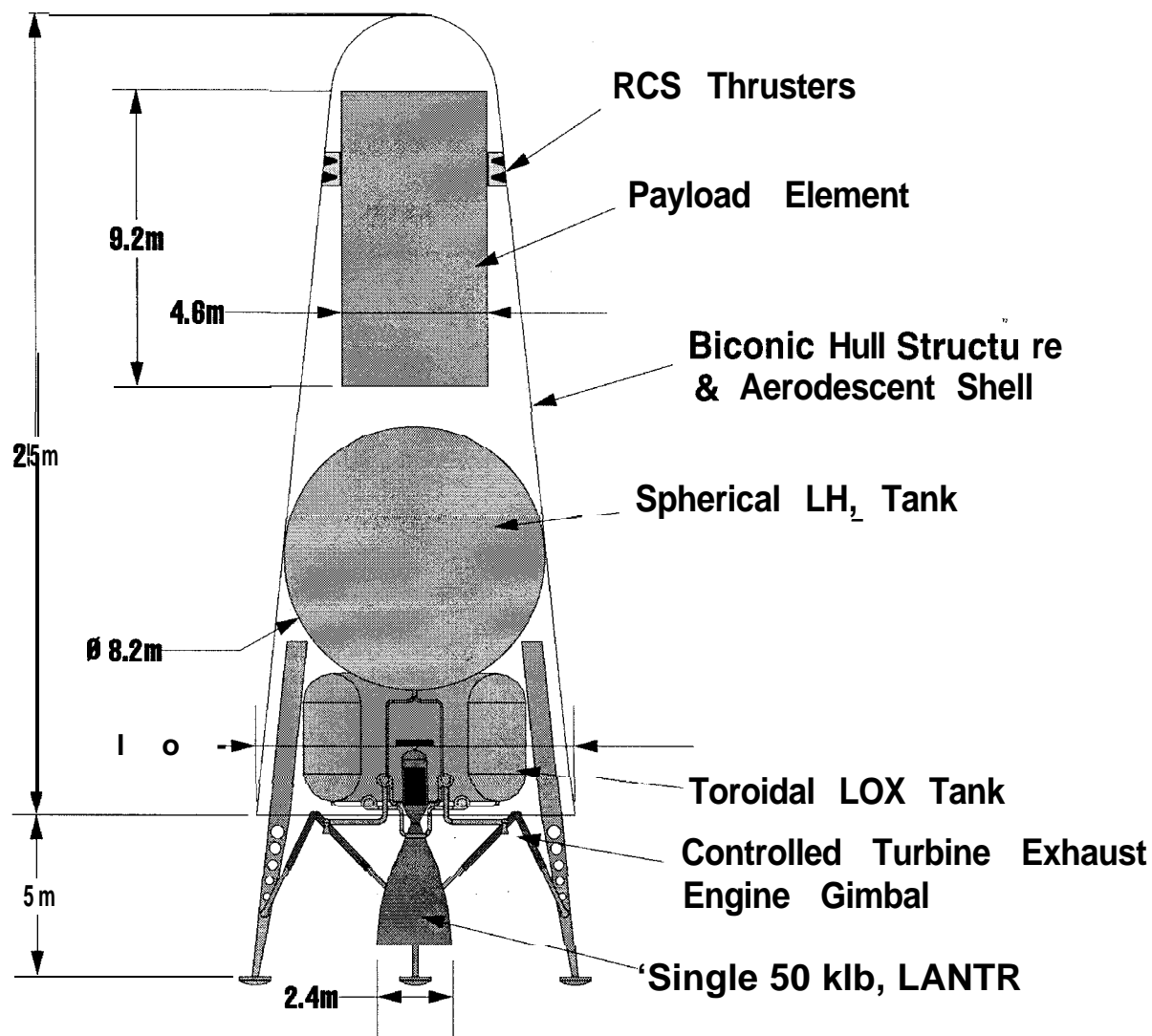


■ Mission possibilities:

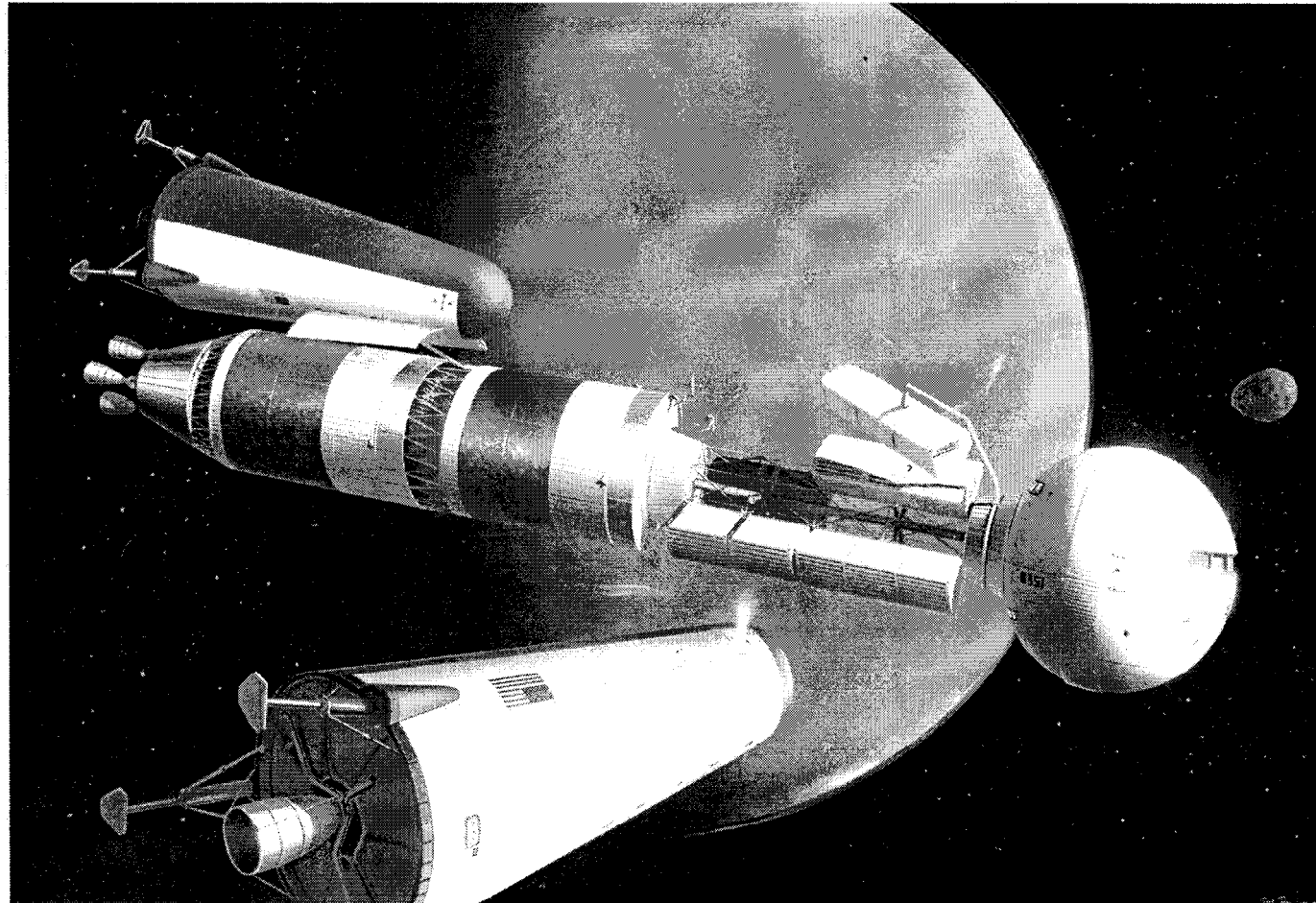
- Reusable Lunar and Mars Transfer Vehicles
- "24 Hour" Commuter Flights to the Moon
- Reusable Mars Ascent/Descent Vehicles

Fully Reusable Mars Ascent / Descent Vehicle (MADV) Powered by LANTR Propulsion

- GLOW ~ 110 t
- Dry Mass ~ 30 t
- Prop Mass ~ 70 t
(MR = 3)
- Payload ~ 10 t
(up & down)



Elements of Fully Reusable NTR-Based Mars Space Transportation System Architecture



*Bimodal LANTR-powered Space Transfer Vehicle (STV) shown unloading modular payload elements.
LANTR-powered Ascent/Descent Vehicles deliver cargo to Mars surface and refuel propellant to STV.*